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Study of breakup and transfer of weakly bound nucleus ^{6}Li to explore the low energy reaction dynamics

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Abstract. Investigation of the breakup and transfer effect of weakly bound nuclei on the fusion process has been an interesting research topic in the past several years. However, owing to the low intensities of the presently available radioactive ion beam (RIB), it is difficult to clearly explore the reaction mechanisms of nuclear systems with unstable nuclei. In comparison with RIB, the beam intensities of stable weakly bound nuclei such as ^{6,7}Li and ^{9}Be, which have significant breakup probability, are orders of magnitude higher. Precise fusion measurements have already been performed with those stable weakly bound nuclei, and the effect of breakup of those nuclei on the fusion process has been extensively studied. Those nuclei indicated large production cross sections for particles other than the $\alpha + x$ breakup. The particles are originated from non-capture breakup (NCBU), incomplete fusion (ICF) and transfer processes. However, the conclusion of reaction dynamics was not clear and has the contradiction.

In our previous experiments we have performed ^{6}Li+^{96}Zr and ^{154}Sm at HI-13 Tandem accelerator of China Institute of Atomic Energy (CIAE) by using HPGe array. It is shown that there is a small complete fusion (CF) suppression on medium-mass target nucleus ^{96}Zr different from about 35% suppression on heavier target nucleus ^{154}Sm at near-barrier energies. It seems that the CF suppression factor depends on the charge of target nuclei. We also observed one neutron transfer process. However, the experimental data are scarce for medium-mass target nuclei.

In order to have a proper understanding of the influence of breakup and transfer of weakly bound projectiles on the fusion process, we performed the ^{6}Li+^{89}Y experiment with incident energies of 22 MeV and 34 MeV on Galileo array in cooperation with Si-ball EUCLIDES at Legnaro National Laboratory (LNL) in Italy. Using particle-particle and particle-γ coincidences, the different reaction mechanisms can be clearly explored.

1 Introduction

Investigation of the breakup effect of weakly bound nuclei on the fusion process has been an interesting research topic in the past several years [1–3]. Several experiments and theoretical calculations have focused on this subject. The situation is more complicated when weakly bound nuclei are involved with respect to tightly bound nuclei. Different processes can occur after the breakup of weakly bound nuclei (usually the projectiles). When all the fragments fuse with target nucleus one by one, this process is called sequential complete fusion (SCF). When only part of the fragments fuses with the target nucleus, this process is called incomplete fusion (ICF). When no any fragments are captured, this process is called non-capture breakup (NCBU). During the fusion process, the whole projectile can also fuse with the target nucleus without breakup, and this process is named as direct complete fusion (DCF). Experimentally, the residues formed in SCF cannot be distinguished from ones from DCF, since the compound nucleus is the same. Therefore, in the experiment the complete fusion (CF) cross sections include the contributions of both SCF and DCF. The total fusion (TF) cross section is equal to the sum of CF and ICF, $\sigma_T = \sigma_{CF} + \sigma_{ICF}$. Besides the above processes, transfer process can also occur such as

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one neutron stripping and pickup. In ICF and transfer processes, the same residual nuclei can be formed. However, in these two processes the light charged particles with different energies can be emitted. In coincidence with the light charged particles, these two processes can be separated.

With the availability of radioactive ion beam (RIB) facilities in a few laboratories, one can produce several kinds of unstable nuclei including neutron- and proton-rich nuclei. Experimental fusion cross sections of unstable nuclei on different target nuclei have been reported. However, owing to the low intensities of the presently available RIB, it is difficult to clearly explore the reaction mechanisms of nuclear systems with unstable nuclei. In comparison with RIB, the beam intensities of stable weakly bound nuclei such as ^{6,7}Li and ^{9}Be, which have significant breakup probability, are orders of magnitude higher. Precise fusion measurements have already been performed with those stable weakly bound nuclei, and the effect of breakup of those nuclei on the fusion process has been extensively studied. It was found that the CF suppression factors at energies slightly above the Coulomb barrier for reactions induced by the same projectile are independent of the charge of target nuclei and mainly depend only on the breakup threshold energy values of the projectile [4, 5]. Wang *et al.* [6], for ^{6}Li with a breakup threshold energy of 1.474 MeV, found an average suppression around 40%. In a recent and very interesting paper [7], an estimate of CF was obtained for the ^{6}Li+^{64}Ni by measuring TF. The derived CF suppression was 13±7%, much smaller than the 40% suppression found for heavier targets.

In ^{8}He+^{197}Au experiment [8], by measuring γ rays which are emitted from the evaporated residual nuclei, fusion and transfer cross sections were obtained. In comparison with the cross sections of these two processes, it is indicated that the sub-barrier total reaction cross section is dominated by one and two neutron stripping. In the case of reactions with neutron-rich radioactive ion beams, the coupling to transfer is found to be important. Recently for the first time in ^{7}Li+^{198}Pt reaction [9] at energies near the Coulomb barrier the α-capture cross sections were measured by in-beam exclusive measurements of prompt γ -rays from the heavy-residues with various light charged particles (α, *t*, *d* and *p*). The cross sections of the residues resulting from the processes of fusion, *t*-capture and neutron transfer channels were measured by off-beam γ methods. The integrated cross sections for the above several channels were obtained. The different processes were distinguished including breakup fusion and the nucleon transfer. The massive transfer of ^{5,6}He for ^{7}Li was also observed and the breakups of ^{6}He+*p* and ^{5}He+*d* were not observed due to the high breakup threshold. The result of a classical dynamic model [10–12] gave a good agreement with the experimental data and explained the critical role of different cluster structures of ^{7}Li in the dynamics of reaction mechanism for the first time. These calculations clearly illustrated a two step process, breakup followed by fusion, in case of the capture of *t* and α clusters. The present results are useful for the theoretical developments. It is important to carry out a systematic investigation on various targets especially for unstable weakly bound nuclei. Very recently Diaz-Torres *et al* start to develop an unified quantum dynamic model to describe the relevant processes (CF, ICF, NCBU and transfer). So this kind of measurements will further push the theoretical development.

2 Experiments and results

Recently at HI-13 Tandem of CIAE, Beijing, we performed the experiments ^{6}Li+^{96}Zr [13] and ^{6}Li+^{154}Sm [15]. The results are shown in Figure 1 (Left) and Figure 2 (Left), respectively. It is found that there is CF suppression of the order of 25%, at energies above the barrier, when compared with the coupled channel calculations for ^{6}Li+^{96}Zr. In Ref. [2] it is remarked that these studies were based on data for relatively heavy targets and for one of the lightest system investigated, ^{6}Li+^{96}Zr, a smaller suppression was found. Thus, the behavior of the suppression factor in collisions of weakly bound projectiles with light and medium mass targets is not fully established. For a reliable conclusion about this subject, new measurements of CF for lighter targets are required. There is an average suppression of the order of 35% for ^{6}Li+^{154}Sm. The present results show that the systematics of the suppression factor observed for ^{6}Li-induced fusion in the heavy mass region may not be consistent in lighter target mass region. The small breakup probability for lighter targets may produce a smaller effect on the fusion cross section than for heavier targets. Because some γ-ray lines were too weak to be used for the cross section determination of ICF, we only can determine the lower limit for the cross sections of ICF. So the lower limit for cross section of TF is given. The lower limit of the TF cross section data is roughly in agreement with the calculations at the highest energies, which indicates that the ICF seems to be responsible for the loss of flux going to CF, and consequently suppressing the CF at this energy region. Since the experimental data in light target mass region are very scarce, then the systematic behavior needs to be further explored.

Figure 1 (Right) shows the cross sections of 1*n*-stripping in comparison with CF cross sections [14]. At energies around the barrier, the cross sections of 1*n*-stripping are similar to CF cross sections. As its excitation function does not drop as fast as the CF excitation function, it is expected that transfer cross sections should be larger than the CF cross section at sub-barrier energies. Here we measured γ -rays feeding the excited states of ^{97}Zr, we only can determine the lower limit of the one-neutron stripping cross section, the other processes were not distinguished yet. Our CRC calculations give results that are slightly lower than the data, suggesting that the reaction mechanism is complicated. Experimentally, one may perform γ-particle coincidence, as we plan to do in the near future. Theoretically, it is still a challenge for a computer code to take into account all possible reaction mechanisms. Figure 2 (Right) shows the comparison of ^{6}Li+^{154}Sm with ^{6}Li+^{144,152}Sm. One can observe

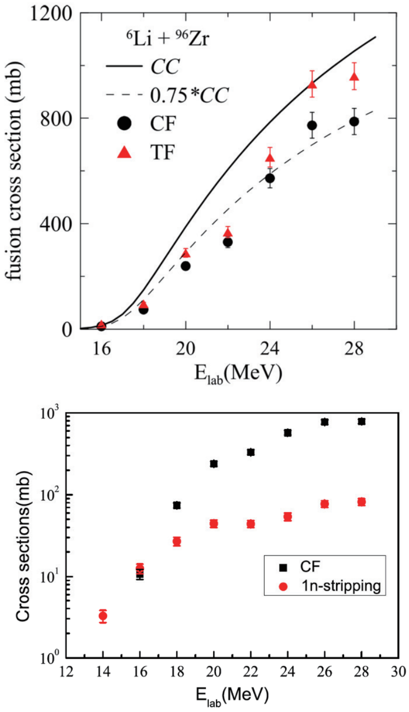

Figure 1. (Up) Complete and total fusion cross sections at energies near Coulomb barrier for ^{6}Li+^{96}Zr [13]; (Down) Measured complete fusion and direct plus two-step 1n-stripping to excited states cross sections corresponding to 1103.1 keV and 1400.1 keV energies for ^{6}Li+^{96}Zr system at near the Coulomb barrier energies [14].

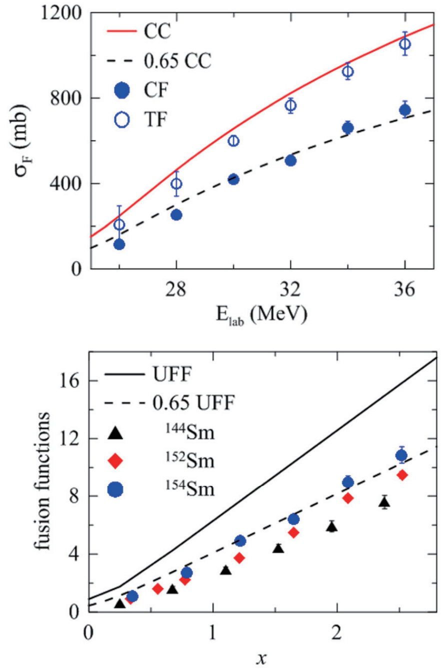

Figure 2. (Up) Complete and lower limit of total fusion cross sections for ^{6}Li+^{154}Sm [15]; (Down) Renormalization experimental fusion functions for the CF of ^{6}Li with three Sm isotopes [15].

that the CF suppressions for the three systems are similar at energies very close to the Coulomb barrier, but when the energy increases, the vibrational ^{144}Sm isotope presents a larger suppression than the deformed ^{152}Sm, and the smallest suppression is found for the most deformed ^{154}Sm. Here we have already taken into account the fact that as the mass A is larger, the size of the system is larger. So, the effect is due to dynamic effects. It is indicated that the breakup effect is larger for the more spherical isotope. The reason for this behavior has to be further investigated both theoretically and experimentally. So the measurement of fusion for more systems is needed.

An experiment using a ^{6}Li beam delivered by the Tandem-XTU accelerator at the LNL (Italy) at E_{lab}=34 MeV and 22 MeV impinging on a ^{89}Y target was performed to study the competition between complete fusion (CF), incomplete fusion (ICF) and transfer reactions. The ^{89}Y target of 550 μg/cm^2 backed on a 340 μg/cm^2 ^{12}C foil was placed at the center of the Galileo γ-ray array [16] coupled to 4π Si-ball EUCLIDES [17–19]. The GALILEO array is made of 25 Compton-Suppressed high-purity germanium detectors distributed on 4 rings: 10 detectors at 90 degrees, 5 detectors at each of the following angles 119, 129 and 152 degrees.

In order to protect the silicon detectors from the extremely high counting rates of elastic scattering, a aluminium cylinder of 200 μm was placed in the center of the

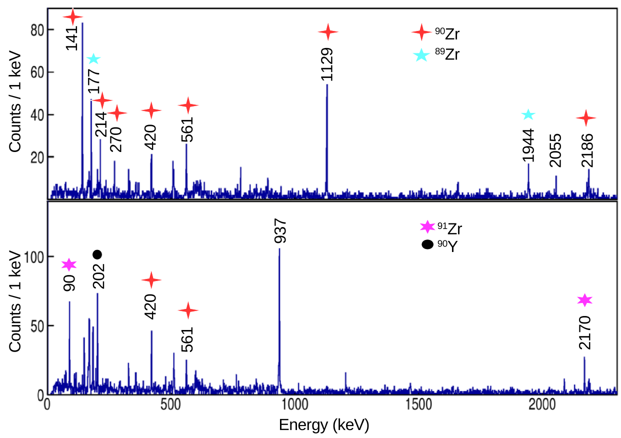

Figure 3. The γ spectra in coincidence with the α particles of the backward (up) and forward (down) angles..

Si-ball in order to completely stop the scattered beam at forward angles. The backward detector of the EUCLIDES Si-ball was left without any absorber. In this setup, the different reaction mechanisms can be easily identified by particle-gamma coincidence. Silicon detectors can be safely run with the beam intensity of ~1.2 enA. The identification of the light-charged particle allows a clear selection of the reaction channel to perform the γ spectroscopy. At the forward angles, the α particles are from transfer when selecting the α particles, the different γ-ray spectrum can be obtained with respect to that of backward angles. In this test experiment we were able to identify the products from transfer, which is shown in Figure 3. The γ rays of ^{90,91}Zr and ^{90}Y can be observed. Then we can derive the cross sections of 1n stripping (^{90}Y), 1p stripping (^{90}Zr) and 1d stripping (^{91}Zr) from the α - γ coincidence. Meanwhile, in the backward alpha-gated γ spectrum, ^{90}Zr, ^{89}Zr and ^{90}Y can be clearly identified. They are related to the components of fusion evaporation residual calculated by PACE4. In two spectra, the γ rays of ^{90}Zr always exists. However, in the backward alpha-gated γ spectrum, the yellow peaks are related to the high lying states of ^{90}Zr, which disappear in the forward alpha-gated γ spectrum. It indicates that the populated states of ^{90}Zr are from the different reaction mechanisms (high lying states from fusion evaporation and low lying states from 1p - stripping reaction). A strong argument is shown that the different reaction mechanisms have been clearly identified by particle - gamma coincidence. According to the above analysis, the present facilities and technology can be applied for this type of experiments.

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